

Muon decay:
Measurement of the
transverse e^+ polarization
and its implications on

- G_F (Fermi coupling constant)
- TRI (time reversal invariance)

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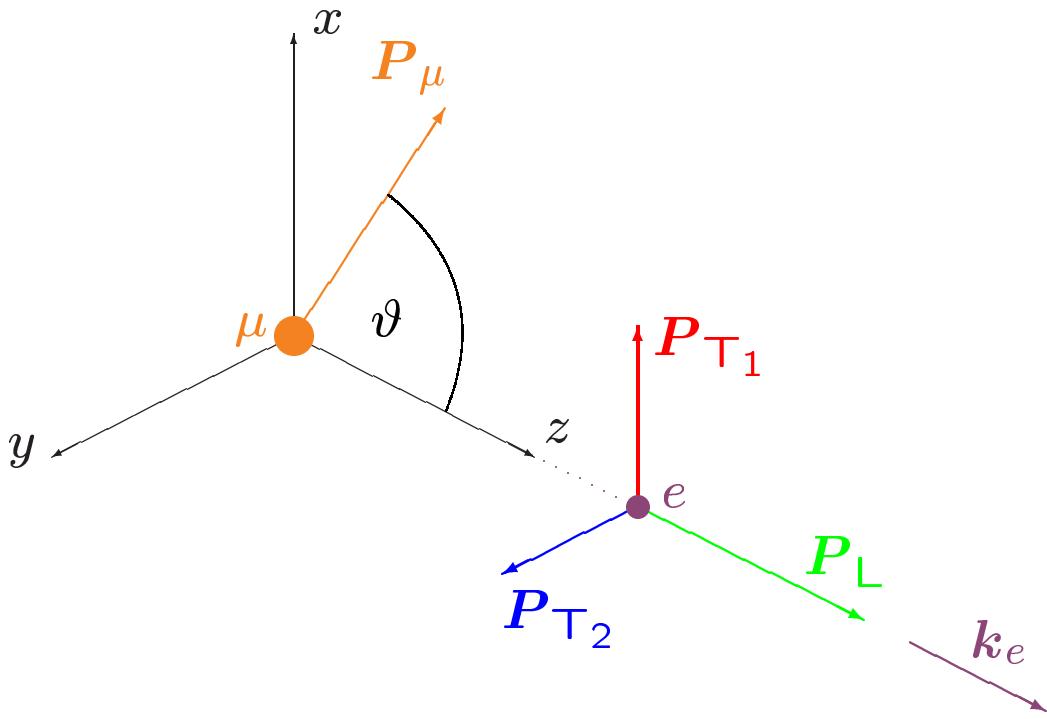
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2. Observables



$$P_{T_1} = f_1(E, \vartheta, \eta, \eta'')$$

$$P_{T_2} = f_2(E, \vartheta, \frac{\alpha}{A}, \frac{\beta}{A})$$

The standard model predicts:

$$\langle P_{T_1} \rangle_E = -3 \times 10^{-3}$$

$$P_{T_2} \equiv 0$$

A nonzero P_{T_2} would signal violation of time reversal invariance. This is the only purely leptonic reaction for which TRI has been tested up to now.

3. Matrix Element

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g_{\varepsilon\mu}^\gamma \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle \bar{\nu}_m | \Gamma_\gamma | (\mu)_\mu \rangle$$

The index γ labels the type of interaction:

$$\Gamma^S = \text{4-scalar}$$

$$\Gamma^V = \text{4-vector}$$

$$\Gamma^T = \text{4-tensor}$$

The indices ε, μ indicate the chiralities of the spinors of the observed (charged) leptons. The chiralities n, m of the neutrinos are uniquely determined for given γ, ε and μ .

The transverse polarization component P_{T_1} yields the low energy parameter η *without* the suppression factor m_e/m_μ of η in the energy spectrum of the decay positron. These interference terms allow for sizeable effects.

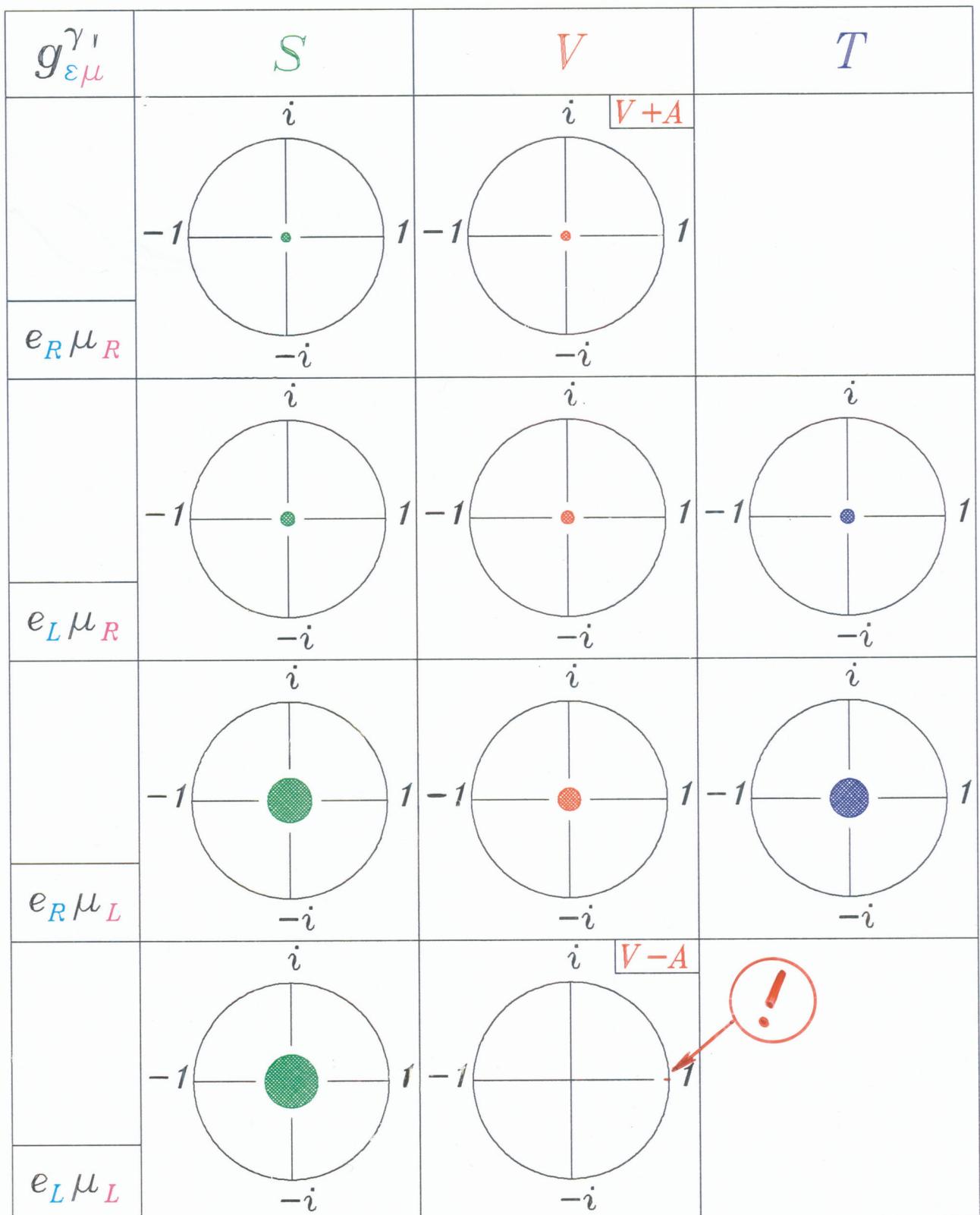
$$\begin{aligned} \eta = & \frac{1}{2} \operatorname{Re} \{ \textcolor{red}{g}_{LL}^V g_{RR}^{S*} + \textcolor{red}{g}_{RR}^V g_{LL}^{S*} \\ & + \textcolor{red}{g}_{LR}^V (g_{RL}^{S*} + g_{RL}^{T*}) + \textcolor{red}{g}_{RL}^V (g_{LR}^{S*} + g_{LR}^{T*}) \} \end{aligned}$$

In the standard model

$$\textcolor{red}{g}_{LL}^V = 1$$

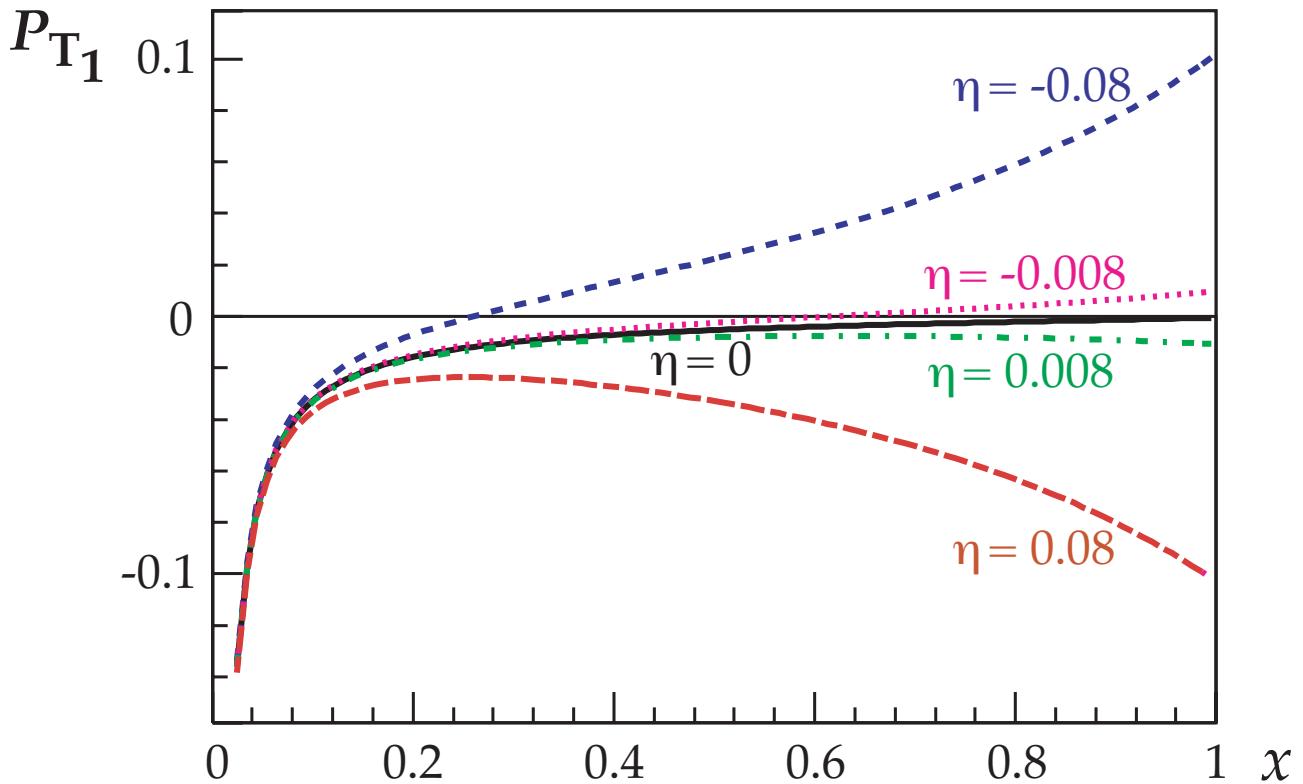
$$g_{\varepsilon\mu}^\gamma = 0 \quad (\text{all other interactions})$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Experimental limits for the normalized coupling

constants $g_{\varepsilon\mu}^{\gamma'} = \frac{g_{\varepsilon\mu}^\gamma}{|g_{\varepsilon\mu}^\gamma|}$.



Assuming 1 additional interaction and knowing that

$$g_{LL}^V \approx 1,$$

one deduces:

$$P_{T_1}(E_e) \rightarrow \eta \approx \frac{1}{2} \operatorname{Re}\{g_{RR}^S\}$$

$$P_{T_2}(E_e) \rightarrow \frac{\beta'}{A} \approx \frac{1}{4} \operatorname{Im}\{g_{RR}^S\}$$

Main scientific interests:

P_{T_1} : Precise determination of Fermi coupling constant G_F

P_{T_2} : Test of time reversal invariance

4. Fermi coupling constant

Should be independent of masses and radiative corrections:

Universal coupling constant

$$G_F^2 = 192\pi^3 \cdot \frac{\hbar}{\tau_\mu} \cdot \frac{1}{m_\mu^5} \cdot \left\{ 1 + \frac{\alpha}{2\pi} \left(\pi^2 - \frac{25}{4} \right) \right\} \cdot \left\{ 1 - \frac{3}{5} \left(\frac{m_\mu}{m_W} \right)^2 \right\} \cdot \left\{ 1 - 4\eta \cdot \frac{m_e}{m_\mu} - 4\lambda \cdot \frac{m_{\nu_\mu}}{m_\mu} + 8 \left(\frac{m_e}{m_\mu} \right)^2 + 8 \left(\frac{m_{\nu_\mu}}{m_\mu} \right)^2 \right\}$$

New:

$$\lambda \approx \frac{1}{2} \operatorname{Re} \left\{ g_{LL}^V \cdot g_{LR}^{V*} \right\}$$

In left-right symmetric models with mixing angle ζ :

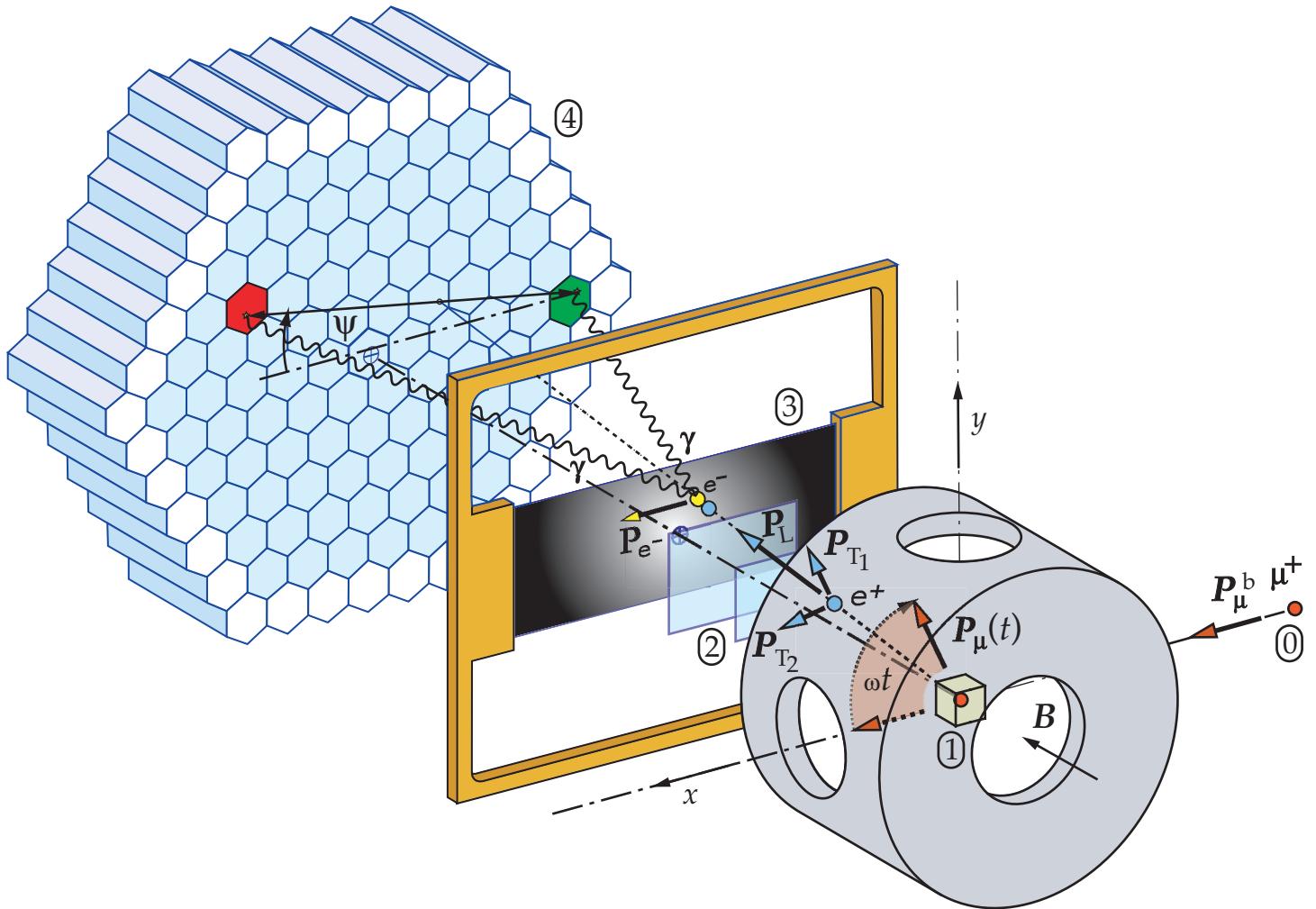
$$\lambda \approx \frac{1}{2} \zeta$$

Contribution from	$\frac{\Delta G_F}{G_F} [10^{-6}]$	
	$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$	$\tau^+ \rightarrow \bar{\nu}_\tau \mu^+ \nu_\mu$
Δm_W	0.0	1
$\Delta m_{\mu,\tau}$	0.2	421
$\Delta \tau$	9.1	2 070
$\Delta(\lambda m_{\bar{\nu}})$	70.0	22 500
$\Delta \eta$	126.0	6 500
$\Delta \Gamma_{\tau \rightarrow \mu}$	-	100 000

5. Experimental setup

- 5.1 Highly polarized μ^+ beam at $\mu E1$ area of PSI: (91%)
- 5.2 Muon stop rate in Be target:
 $(20 - 80) \times 10^6 \text{ s}^{-1}$
- 5.3 Precession in homogeneous B field;
precession frequency = cyclotron frequency
(50.8 MHz)
- 5.4 Burst width 3.9 ns (FWHM)
 \implies 80% muon polarization in Be stop target
- 5.5 Positron tracking with drift chambers
- 5.6 Annihilation with polarized e^-
- 5.7 Detection of annihilation quanta with 127 BGO crystals

Setup of the Experiment and Principle of Measurement

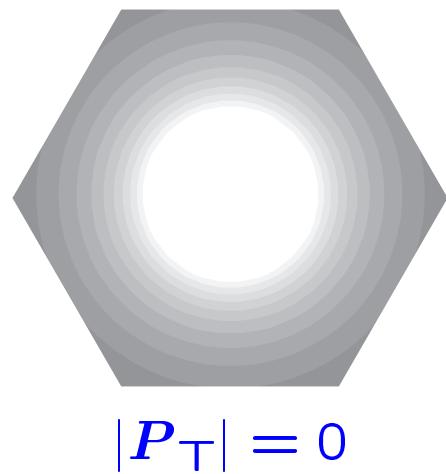


- 0: Burst of polarized muons
- 1: Be stop target
- 2: Plastic scintillators
- 3: Magnetized Vacoflux foil
- 4: 127 BGO scintillators

Measurement of $|P_T|$:

We make use of the dependence of the annihilation cross section on the relative orientation of the spins.

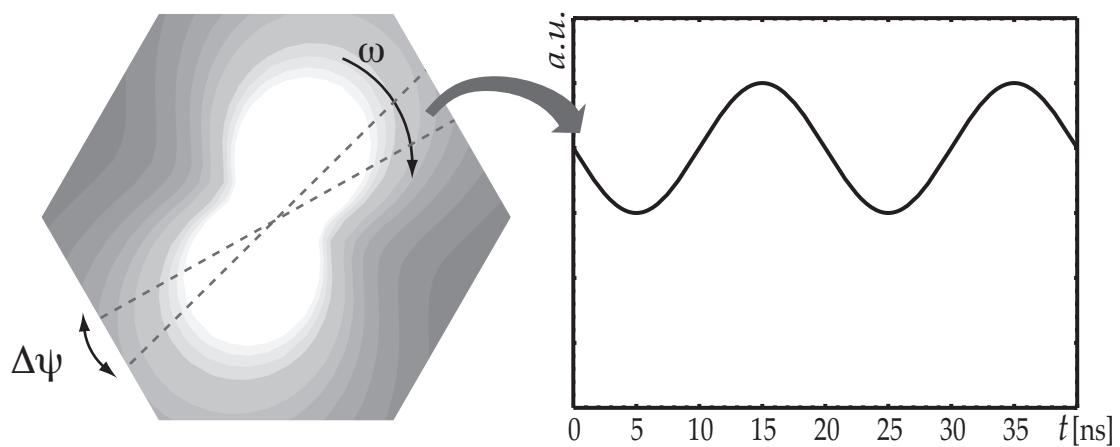
Simulation of photon intensity distributions in the BGO calorimeter: BGO-Kalorimeter :



Simplifying assumptions :

$$e^- \text{- polarization} = 100\%$$

$$E_{\gamma 1} = E_{\gamma 2} = 10 \text{ MeV}$$

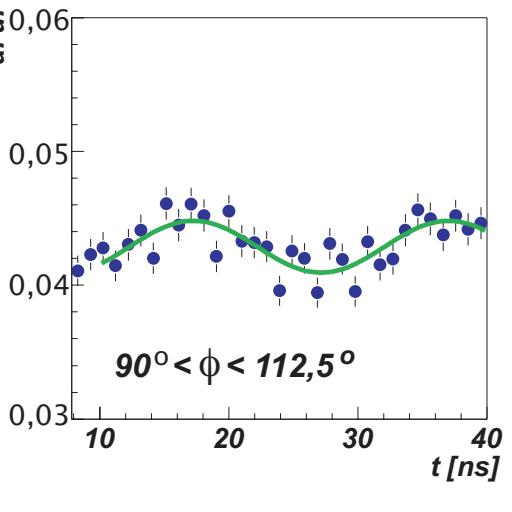
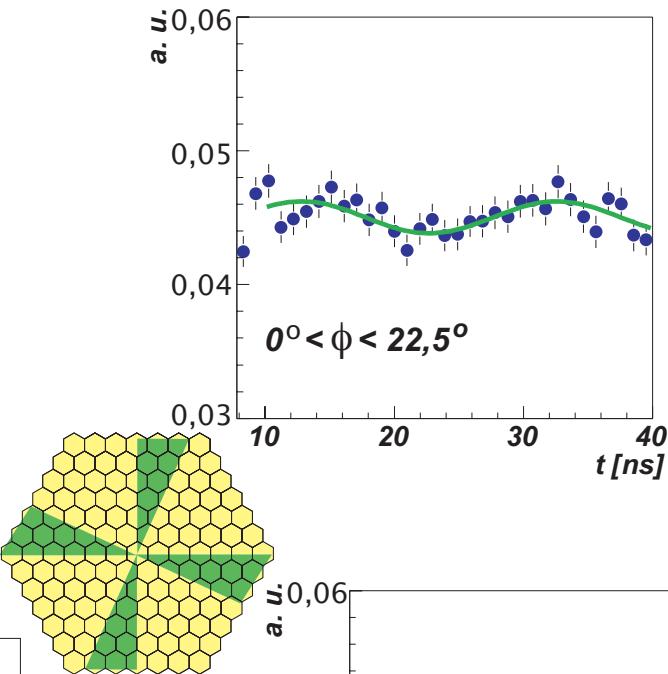
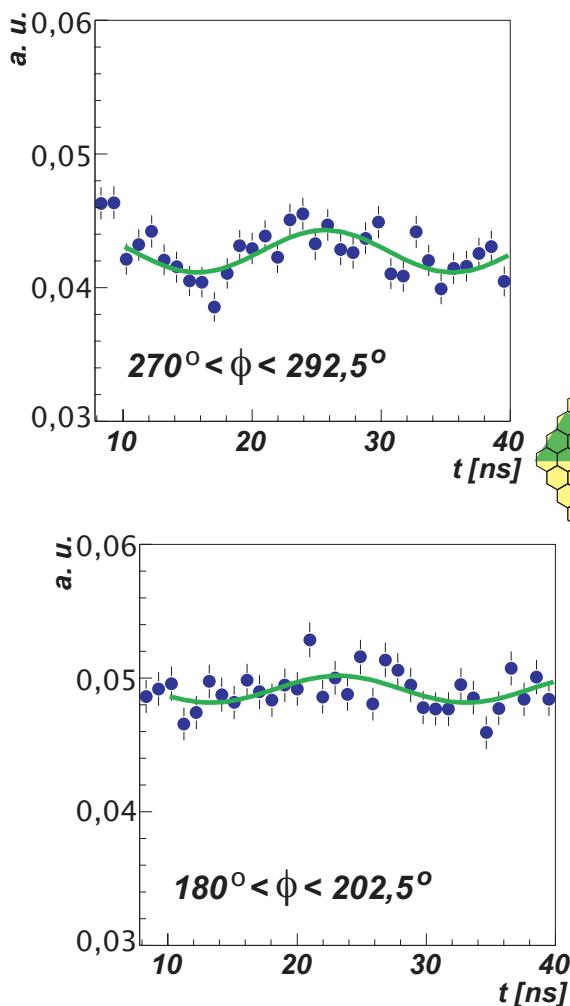


$$|P_T| = 1$$

Time spectrum for a given detector region $\Delta\psi$.

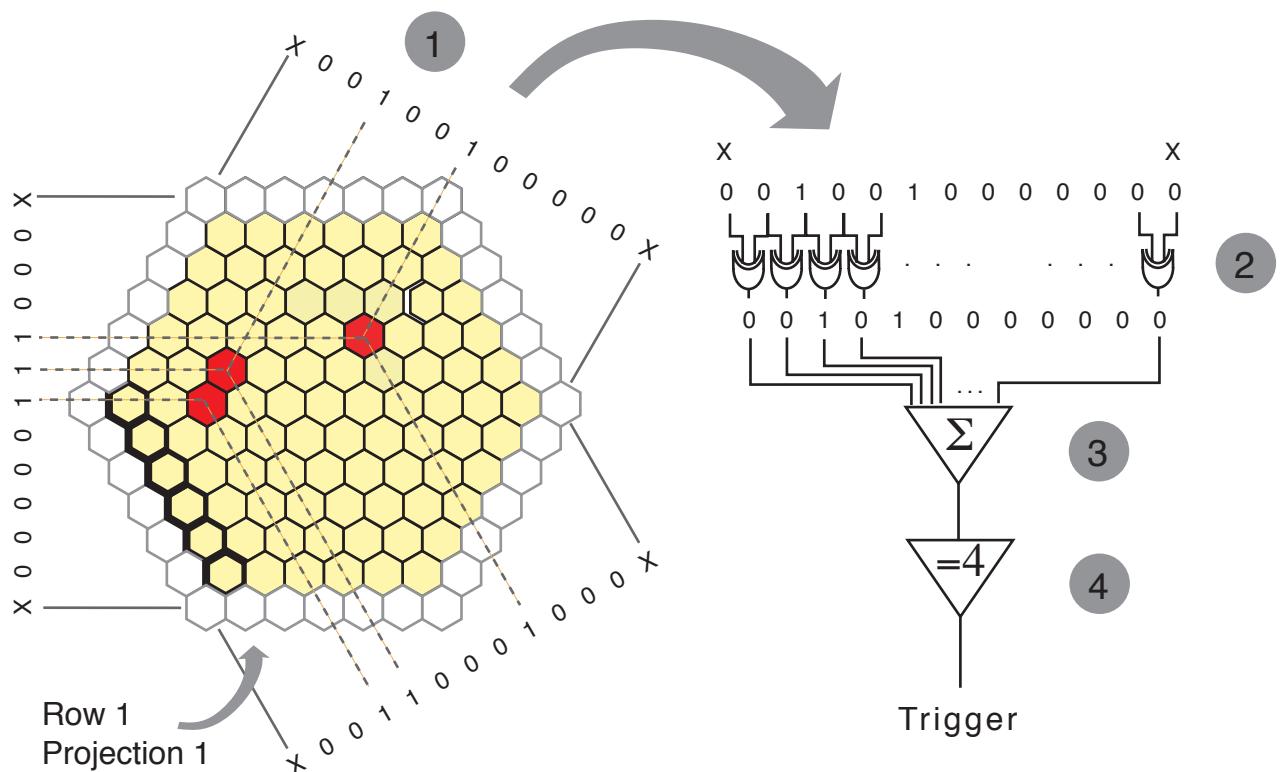
Measurement of the phase φ of P_T :

Time variation of the photon intensity for selected angles of emission of the e^+ . Effect due to μ^+ decay asymmetry und μ SR :



⇒ Relation Time \leftrightarrow Direction of μ^+ polarization

6. Experimental details



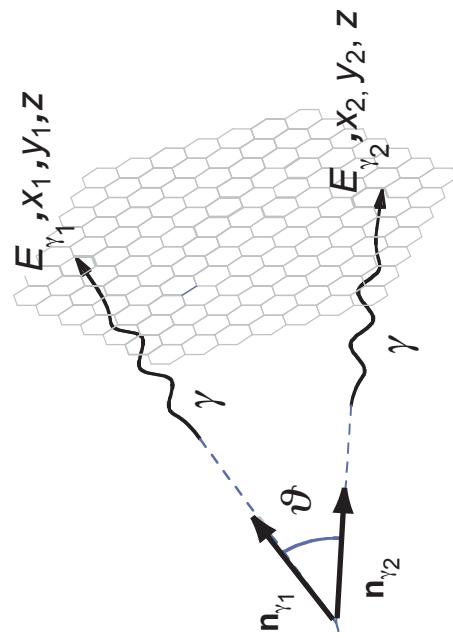
$$\cos \vartheta_{\min} = 1 - 4 \frac{m_e}{E_{e+}}$$

$$d = 2z \tan \frac{\vartheta}{2}$$

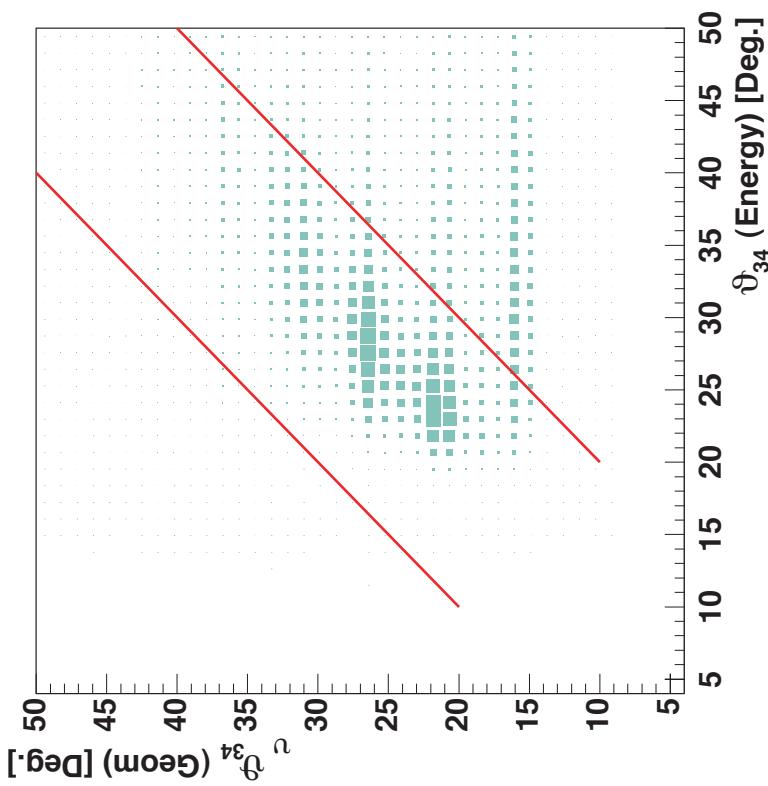
$d_{\min} \approx 160$ mm

Cut on the Kinematics to Extract the 'Good' Events

Calculate ϑ in two different ways:



Sample from the last run



Energy:

$$\cos \vartheta = 1 - m_e \frac{E_{\gamma_1} + E_{\gamma_2}}{E_{\gamma_1} \cdot E_{\gamma_2}}$$



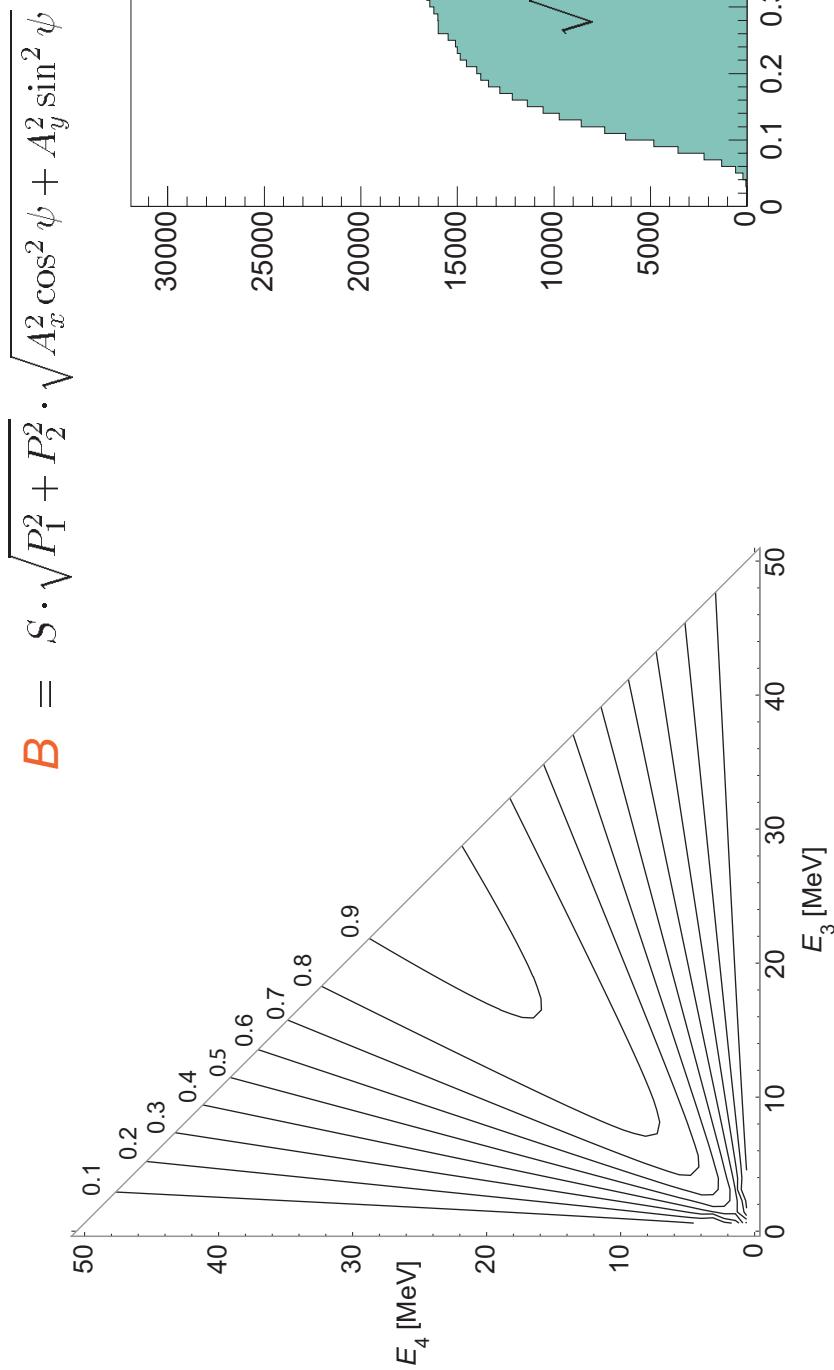
Geometry:

$$\vartheta^{Geom} = \vartheta^{Energy}$$

$$\cos \vartheta = \vec{n}_{\gamma_1} \cdot \vec{n}_{\gamma_2}$$

for 'good' annihilations

Analyzing Power A and amplitude B of oscillation



Theoretical analyzing power,
 $\psi = 90^\circ$

Analyzing Power of 'good' annihilation events, A_x and A_y are functions of the photon energies.

7. Data analysis

How can we extract the e^+ transverse polarization (P_x, P_y) from the data?

Harmonic oscillation:

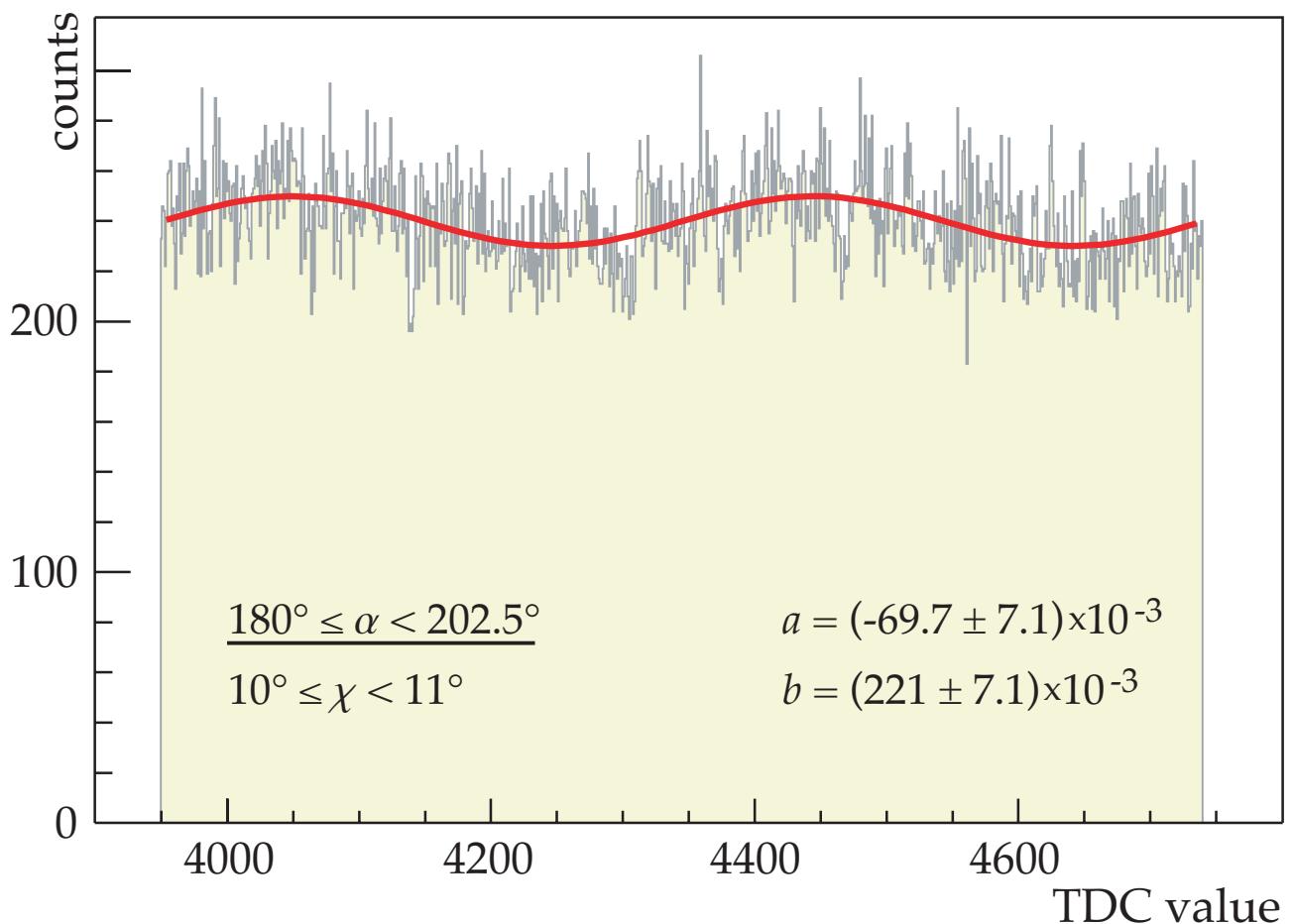
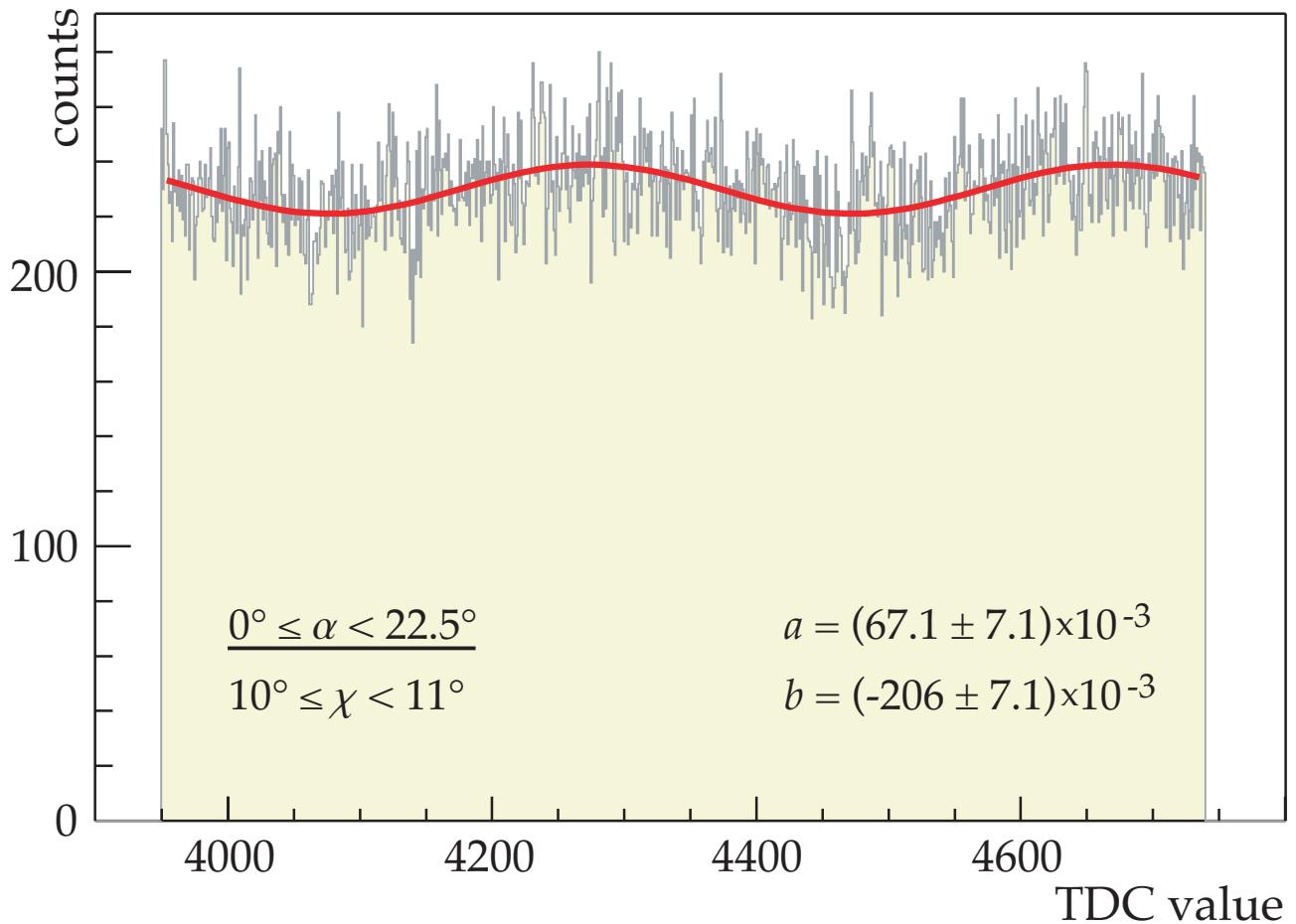
$$\begin{aligned} F(t) &= 1 + \textcolor{brown}{a} \cos \omega t + \textcolor{brown}{b} \sin \omega t \\ &= 1 + A_F \cos(\omega t - \varphi) \end{aligned}$$

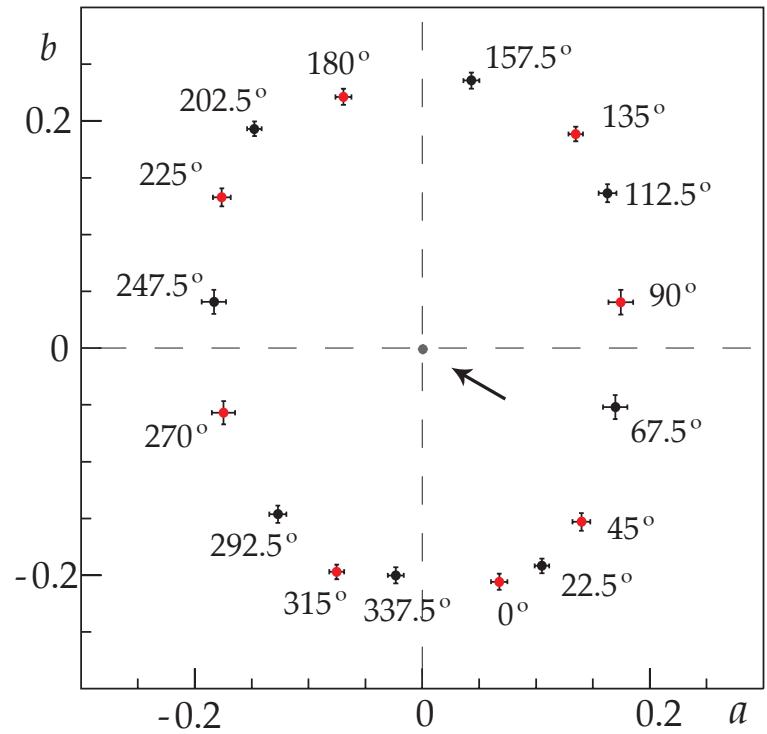
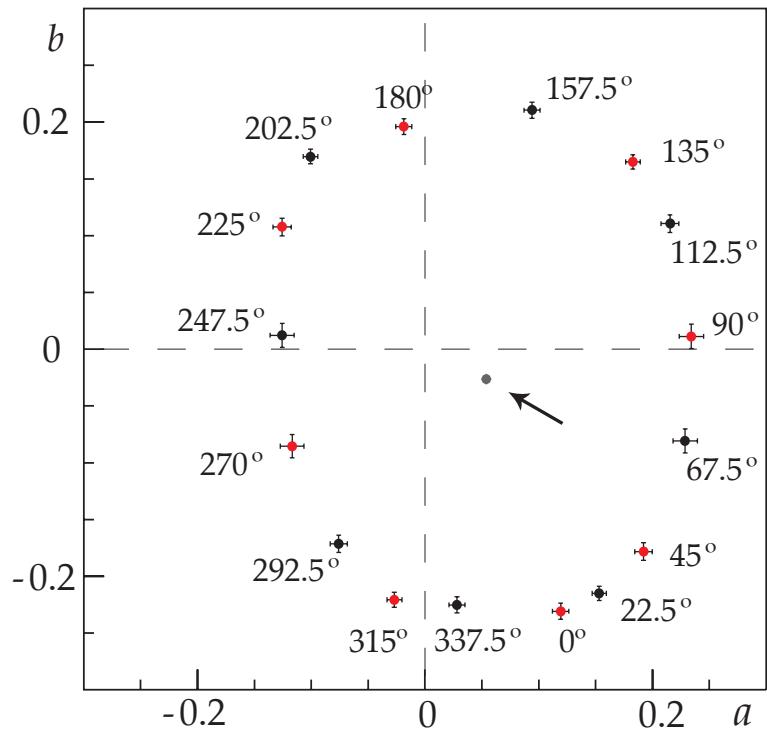
Solution: Fourier analysis; neglect multiples of ω .

$$R(t) = F_{\text{res}}(t) \cdot F_{\mu\text{SR}}(t) \cdot F_{\gamma\gamma}(t)$$

	$\alpha \rightarrow \alpha + 180^\circ$	$P_{e^-} \rightarrow -P_{e^-}$	$A_F [10^{-3}]$
F_{res}	+	+	8.3
$F_{\mu\text{SR}}$	-	+	20.0
$F_{\gamma\gamma}$	+	-	0.3

Symmetry behavior of the three functions F_j .



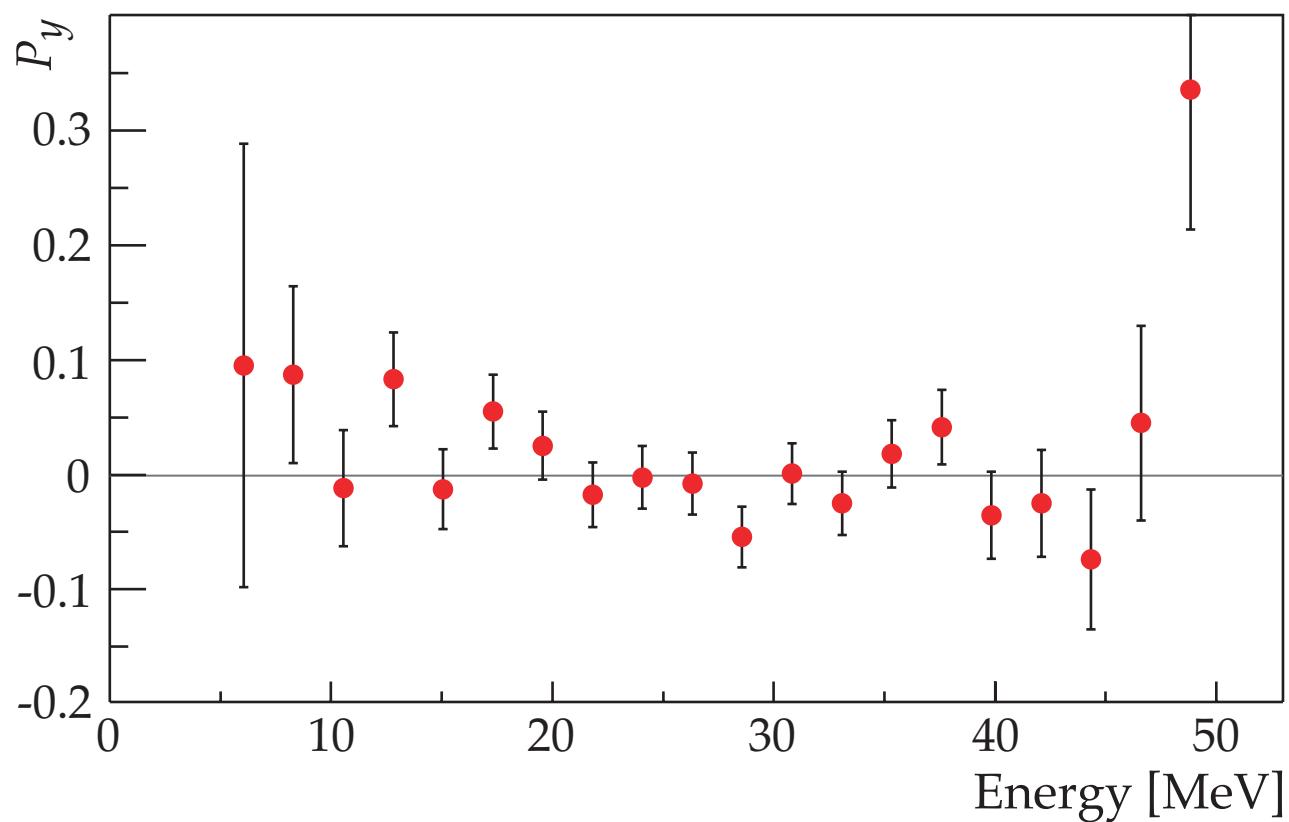
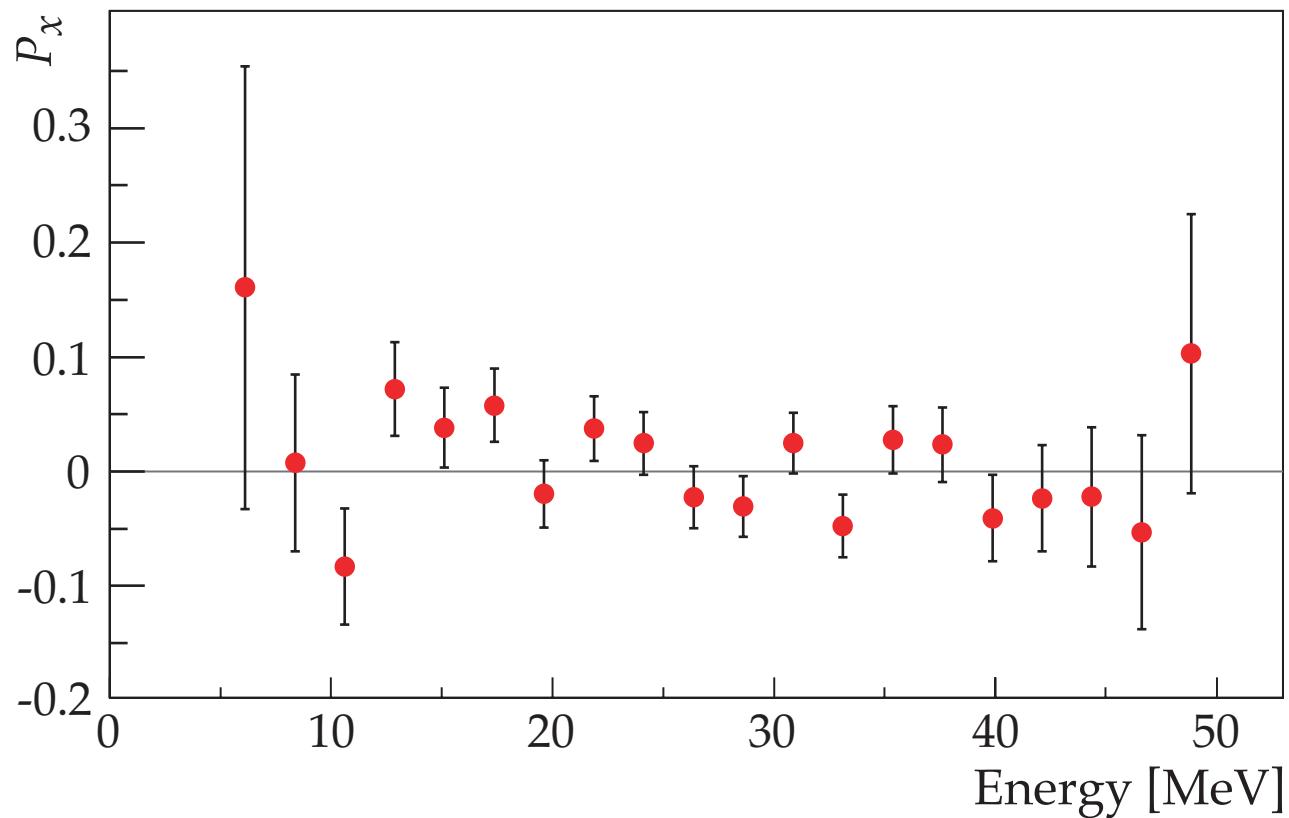


Fourier coefficients $a_{\mu SR}(\alpha)$, $b_{\mu SR}(\alpha)$

Upper figure: Without correction

Lower figure: (a_{res} , b_{res}) subtracted.

Transverse e^+ polarization components
at the moment of annihilation.



8. Results

Systematic errors:

Main sources:

- Energy loss and spin precession
- Background (mainly from bremsstrahlung)
- Values of P_μ und P_{e^-}
- Energy calibration of the BGO detectors

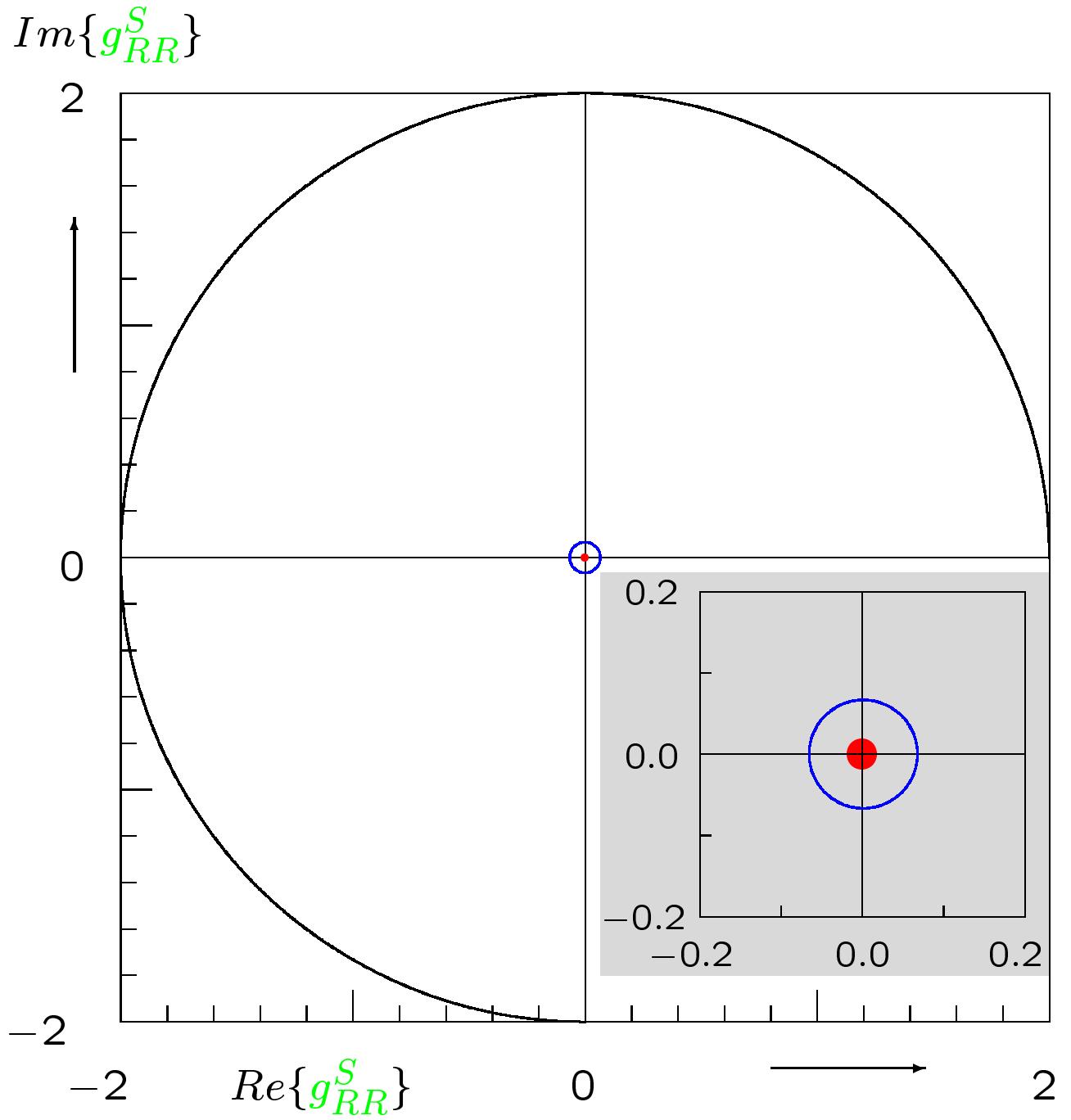
e^+ transverse polarization at the moment of μ^+ decay:

$$\langle P_{T_1} \rangle_E = \frac{\pi}{48} (-9\eta + 7\eta'')$$

$$\langle P_{T_2} \rangle_E = \frac{\pi}{12} \left(\frac{3\alpha'}{A} + 8\frac{\beta'}{A} \right)$$

Final results (in units of 10^{-3}):

	<u>General analysis</u>	<u>Restricted analysis</u>
η	$71 \pm 37 \pm 7$	$-1.8 \pm 7.0 \pm 1.3$
η''	$105 \pm 52 \pm 8$	$\equiv -\eta$
α'/A	$-3.4 \pm 21.3 \pm 5.5$	$\equiv 0$
β'/A	$-0.5 \pm 7.8 \pm 2.0$	$-1.4 \pm 3.5 \pm 0.8$
$\langle P_{T_1} \rangle$	$6.3 \pm 7.7 \pm 3.5$	—
$\langle P_{T_2} \rangle$	$-3.7 \pm 7.7 \pm 3.5$	—



Limits for scalar coupling g_{RR}^S .

Black (outer) circle: by definition.

Blue circle: previous measurement [1]

Inner red circle: this measurement.

Position of red circle: not yet determined.

9. Conclusions

- Experiment to measure the transversal polarization of positrons and the decay parameters for the decay of polarized muons.
- New experimental limits for $\langle P_{T_1} \rangle_E$, $\langle P_{T_2} \rangle_E$ (Improved by a factor of 3) and η , η'' , $\frac{\alpha'}{A}$, $\frac{\beta'}{A}$ (Improved by a factor of 2)
- New experimental limits for scalar right-handed couplings
- Determination of the model-independent Fermi coupling constant G_F
 - All results are in agreement with the standard model
 - Improved limits for the violation of time reversal invariance.